Quantum mechanic and Particle physics

The particle view of nature

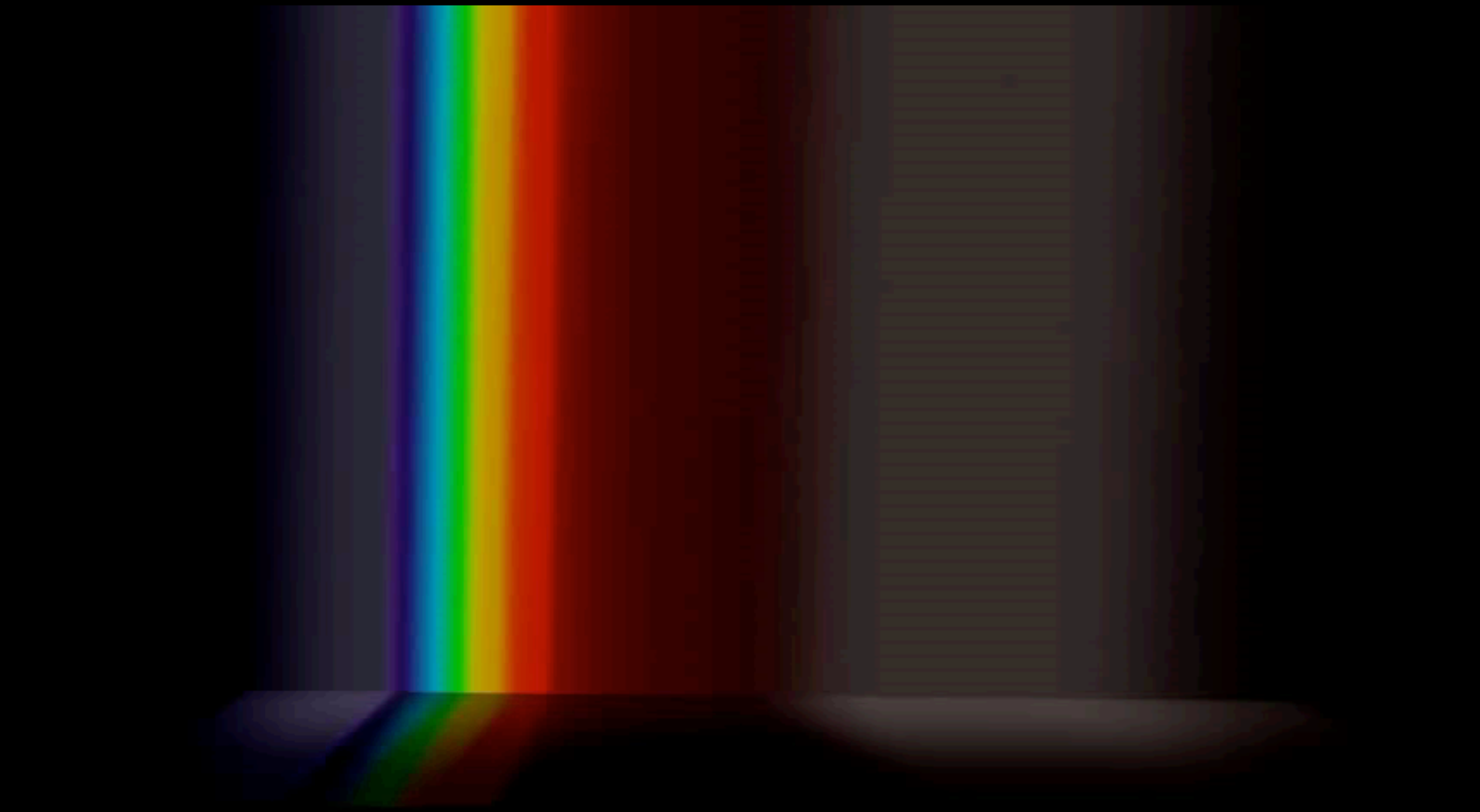
Fields and particles

- In the early part of the 20th century, it seemed like fields had a major role to play in our understanding of nature.
- Electromagnetism and light were understood as taking place within an electromagnetic *field*. Einstein recast gravity as taking place within time-space, conceived of as a field.
- The discovery of quantum mechanics, however, lead to the attempt to recast these theories in terms of particles. Quantum electrodynamics has been very successful, quantum gravitation, less so.

Blackbody Radiation

- A blackbody absorbs light of every wavelength and grows warmer as function of this radiation. When a blackbody is heated it should emit all wavelengths.
- The spectrum of radiant heat was studied (at the Physikalisch-Technische Reichsanstalt) for its application in the lighting and heating industries.
- There were significant discrepancies between the *prediction* based on the assumption continuous radiation and the experimental values.

Blackbody Radiation



Energy Quanta

- Max Planck (1858-1947) introduced *energy quanta* (discrete packets of energy) as a purely theoretical device, to explain the experimental values of blackbody radiation.
- Using a statistical model based on Boltsmann's methods, he modeled the energy of the body as a statistical characteristic of set of unknown 'resonators.' $\varepsilon = n h \nu$, energy is equal to frequency of vibration, ν, times a constant, h, and some whole number n=0,1,2,3…
- This quantum discontinuity, n=0,1,2,3…, was at first not considered physically important. It was a just a simplifying assumption that produced an accurate radiation law.

- Plank, 1931: “By then I had been wrestling unsuccessfully for six years with the problem … and I knew it was of fundamental importance to physics… A theoretical interpretation therefore had to be found at all costs, no matter how high… The new approach was opened to me by maintaining the two laws of thermodynamics… I was ready to sacrifice every one of my previous convictions about physical laws. Boltzmann had shown how thermodynamic equilibrium is established by means of a statistical equilibrium, and if such an approach is applied to the equilibrium between matter and radiation, one finds that the continuous loss of energy into radiation can be prevented by assuming that energy is forced, at the onset, to remain together in certain quanta. This was a purely formal assumption and I did not really give it much thought.”

Einstein's Contribution

- "The Photoelectric Effect," 1905.
- When high energy light shines on a metal plate, the plate emits electrons. The rate of emission is a function of the wavelength of the light. [The function has a series of maxima around certain wavelengths.]
- Einstein's paper was a simple argument that this experimental fact could be explained on the basis of Planck's quanta of energy radiation, and showed again how his constant, *h,* could be calculated.

Solvay Conference, 1911

Niels Bohr (1885-1962)

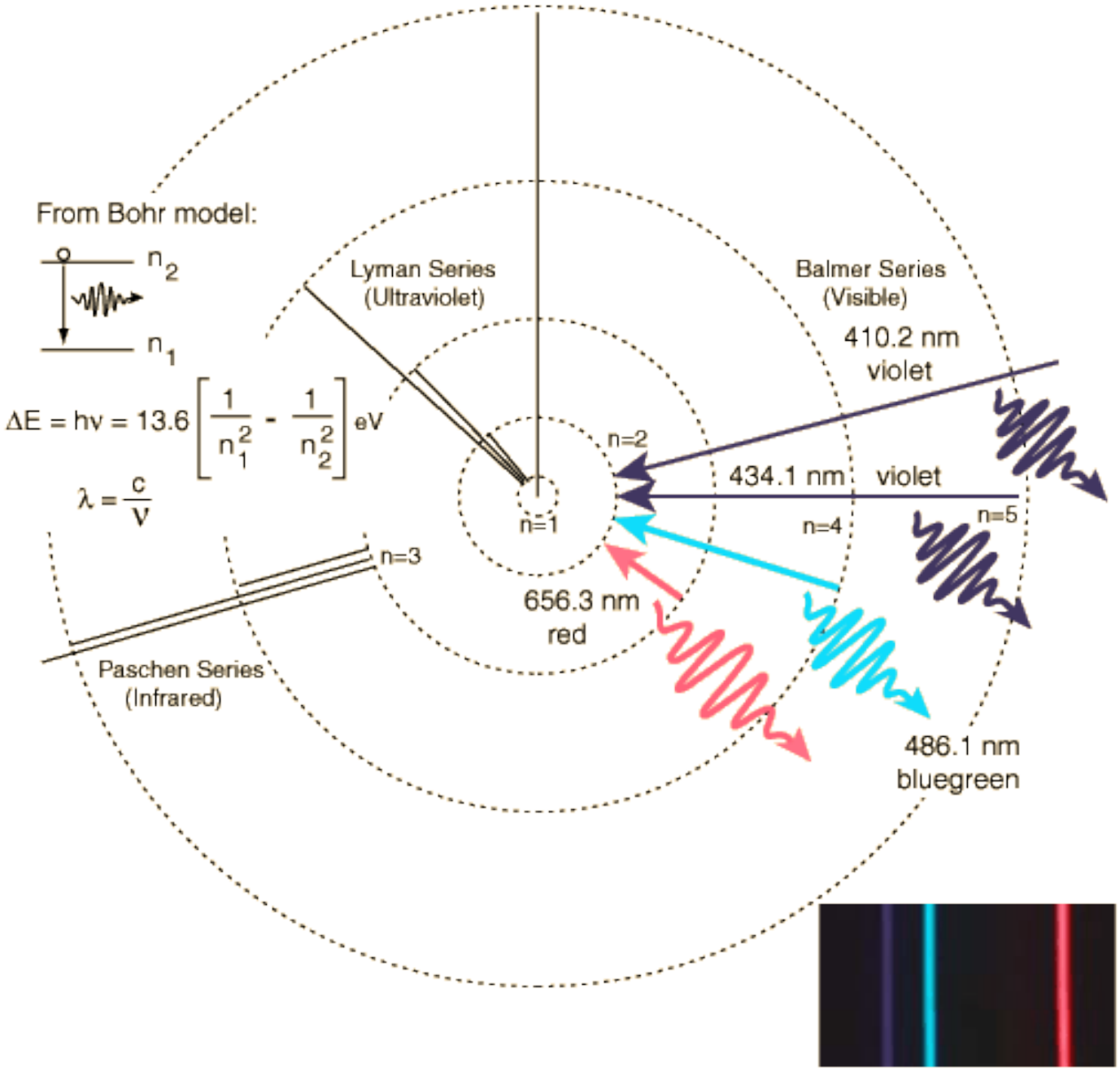
- Born into an academic Dutch family.
- Educated at Copenhagen. Did a postdoc with Rutherford in Manchester University.
- Developed a quantum theory of the atom.
- Professor at Copenhagen. Director of the Institute for Theoretical Physics.
- Nobel Prize in physics 1922.
- Wrote prolifically on the philosophical interpretations and implications of quantum theory. Became the most famous advocate of the "Standard (Copenhagen) Interpretation." Argued for the fundamental indeterminacy of the atom, especially with Einstein.

Rutherford's Atom

- Rutherford's atom was a mechanical system like planets in orbit.
- As the electrons radiated electromagnetic energy (light) they should lose speed and eventually collapse into the nucleus. (That is, they should emit energy to the surrounding systems, atoms, etc.)
- Bohr realized he could use Planck's quanta to stabilize these orbits.
- During this process, a colleague pointed out that his model should also account for spectral lines of chemical elements.

Bohr's Atomic Model

- "On the Constitution of Atoms and Molecules," 1913-15. (In three parts.)
- Bohr set the electrons orbiting around the nucleus only at set intervals. When they were in those prescribed positions they obeyed the laws of classical mechanics but when they absorbed or emitted electromagnetic radiation they did so in *quantum jumps*.
- Bohr, 1913: "The dynamical equilibrium of the systems in the stationary states is governed by the ordinary laws of mechanics, while those laws do not hold for the transition from one state to another."


From Bohr model:
n_2
n_1
$\Delta E = h\nu = 13.6\left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right]$ eV
$\lambda = \frac{c}{\nu}$
Lyman Series
(Ultraviolet)
Balmer Series
(Visible)
410.2 nm
violet
434.1 nm
violet
656.3 nm
red
486.1 nm
bluegreen
Paschen Series
(Infrared)
n=1
n=2
n=3
n=4
n=5

The Implications of the Model

- Bohr was able to use his model to give an explanation of the red and bluegreen spectral line for hydrogen. He predicted further lines in the ultraviolet range. These were found the next year.
- The model, however, indicated that atoms have fundamental behaviors which are unlike anything we encounter with ordinary objects.
- Both light radiation and electrons seem to exhibit some *wave* characteristics and some *particle* characteristics. But the mathematics and mechanics of ordinary waves and particles is very different.
- Moreover, there seems to be no way to actually visualize these atoms.

- Bohr to Heisenberg: “There can be no descriptive account of the structure of the atom; all such accounts must necessarily be based on classical concepts which no longer apply. You see that anyone trying to develop such a theory is really trying the impossible. For we intend to say something about the structure of the atom but lack a language in which to make ourselves understood… In this sort of situation, a theory cannot ‘explain’ anything in the strict scientific sense of the word. All it can hope to do is reveal connections and, for the rest, leave us to grope as best we can.”

Quantum Objects

- Quantum objects, like electrons and photons and all subatomic particles, have a strange kind of behavior that we could not predict by studying the macroscopic world around us.
- Particle like behavior: under some circumstances, quantum objects do things that are similar to ordinary particles.
- Wave like behavior: under other circumstances they do thing like ordinary waves.
- Indeterminate behavior: some things about quantum particles are indeterminate, but not totally random. (Decay time, position and momentum, undetected path, etc.)

Quantum Mechanics

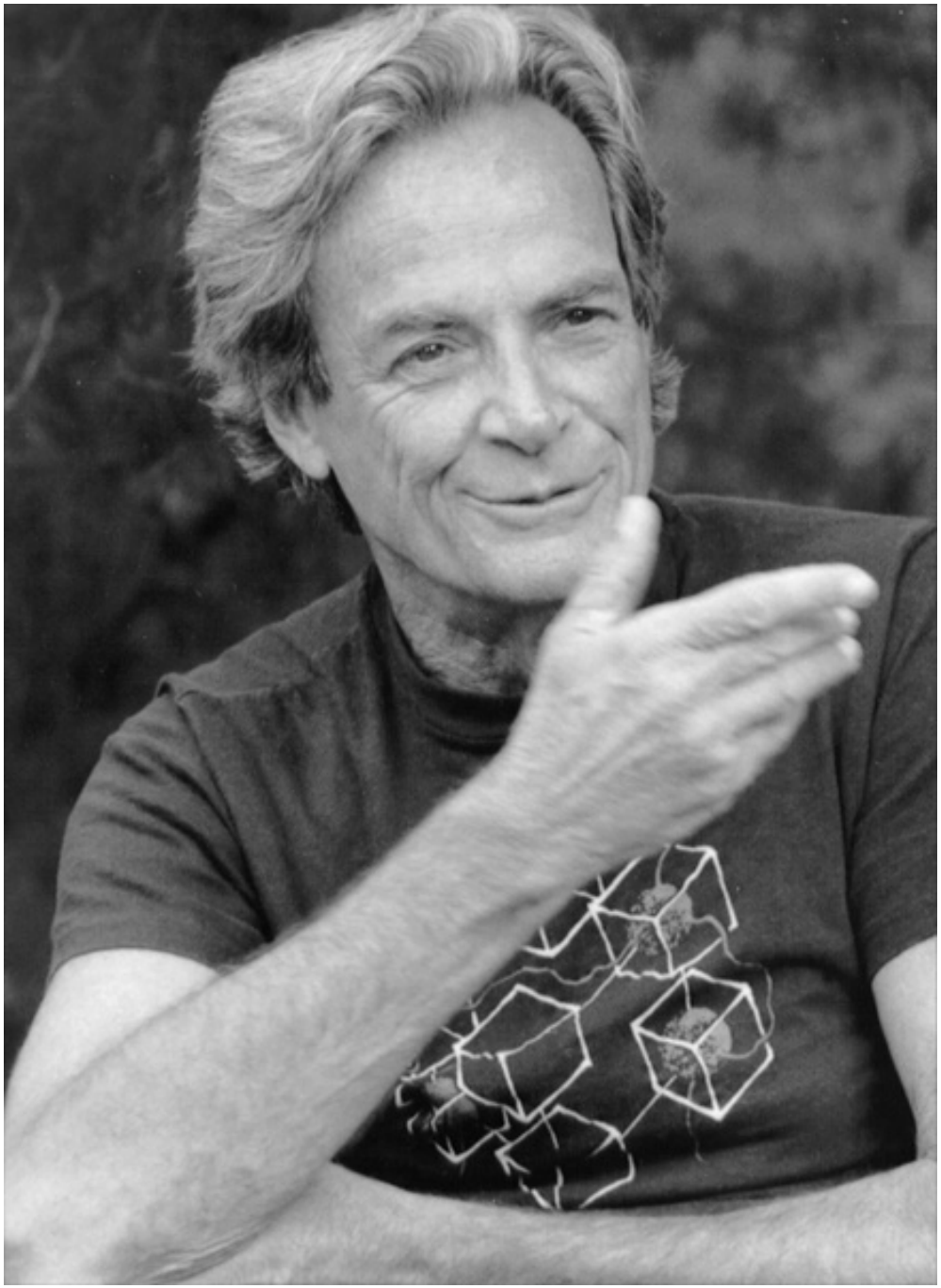
- Developed over a long period of time by many young physicists, such as Bohr, Born, Heisenberg, Pauli, Schrödinger and Dirac.
- Quantum mechanics is a set of mathematical principles and rules that apply to quantum objects.
- It is a highly abstract theory that attempts to formulate the quantum behavior of sub-atomic processes through mathematical models that can be used to predict the probabilities of various outcomes.
- Quantum mechanics has led to quantum electrodynamics, solid state physics, the explication of the chemical bond, high energy particle physics, and theories of quantum gravity (so far, incomplete).

QED

- Quantum electrodynamics was developed by Dirac, Dyson, Feynman, Schwinger, and Tomonaga and others.
- It describes all electromagnetic phenomena as interactions of photons and electrons, treated as purely quantum objects.
- The theory has been essential to all of the advances in chemistry and material sciences, which has led to molecular biology, computer sciences, etc.

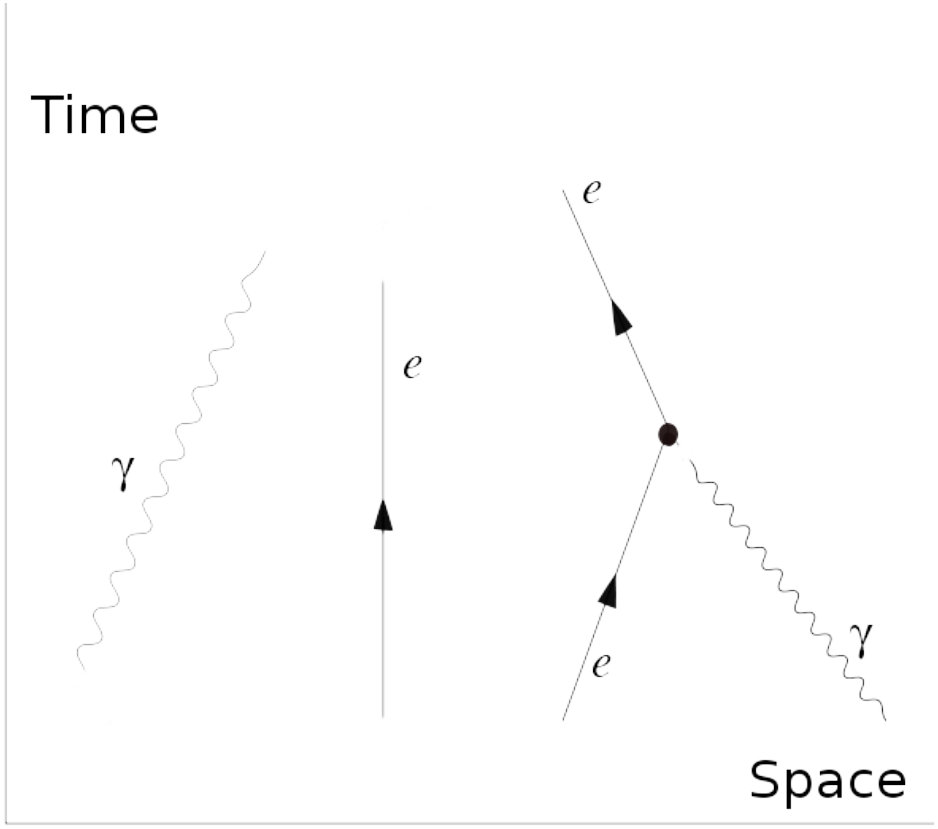
Feynman diagrams

- Quantum interactions are described by complex mathematical models that are difficult to think through.
- This problem was addressed by Richard Feynman by developing schematic diagrams that represent various interactions.
- The diagrams themselves can be subjected to various operations which then correspond to an interaction that may, or may not, occur - depending on other factors, like energy and charge conservation, etc.
- Physicists now use Feynman diagrams as an essential tool for thinking about and modeling quantum behavior.



Encoding information

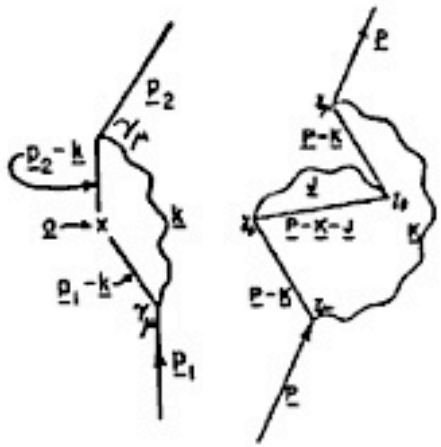
- Different types of particles are represented by different types of lines (γ=photons, *e*=electrons).
- Some particles have charge, represented by an arrow.
- We can manipulate the figure in certain proscribed ways to generate new possible events (but they must conserve energy, charge, etc.)



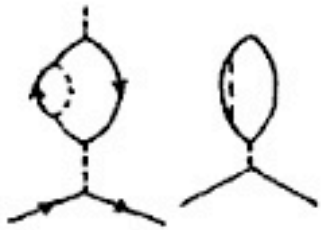
Developing new understandings

- Although the diagrams simply encode the information of the model, they also helped physicists think about these events in a new way and develop new understandings of the processes.
- For example, in neutron decay, a neutron is transformed into a proton, an electron and an anti-neutrino. On the other hand, when a neutrino collides with a neutron, it produces a proton and an electron.
- We can think of an anti-particle (say a positron), as simply a particle (an electron) with its charge orientated the opposite way with respect to time.

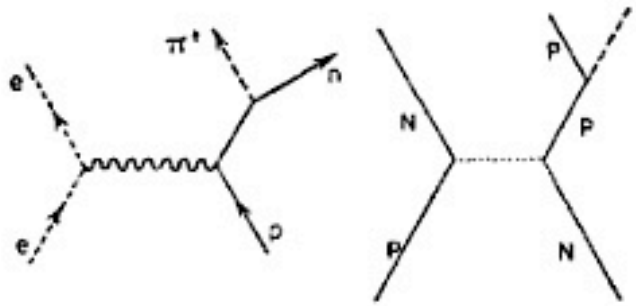
Cornell



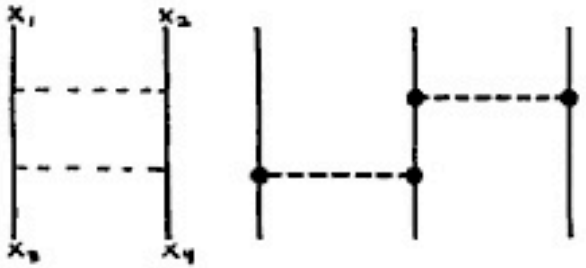
Columbia



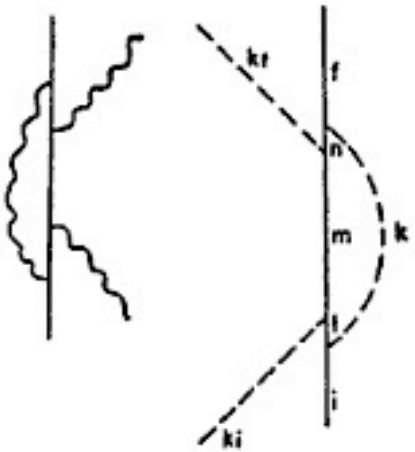
Rochester



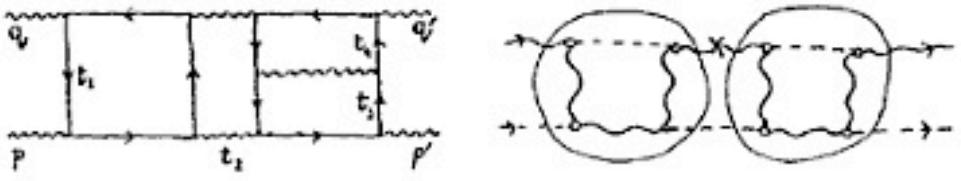
Chicago



Urbana



Oxbridge

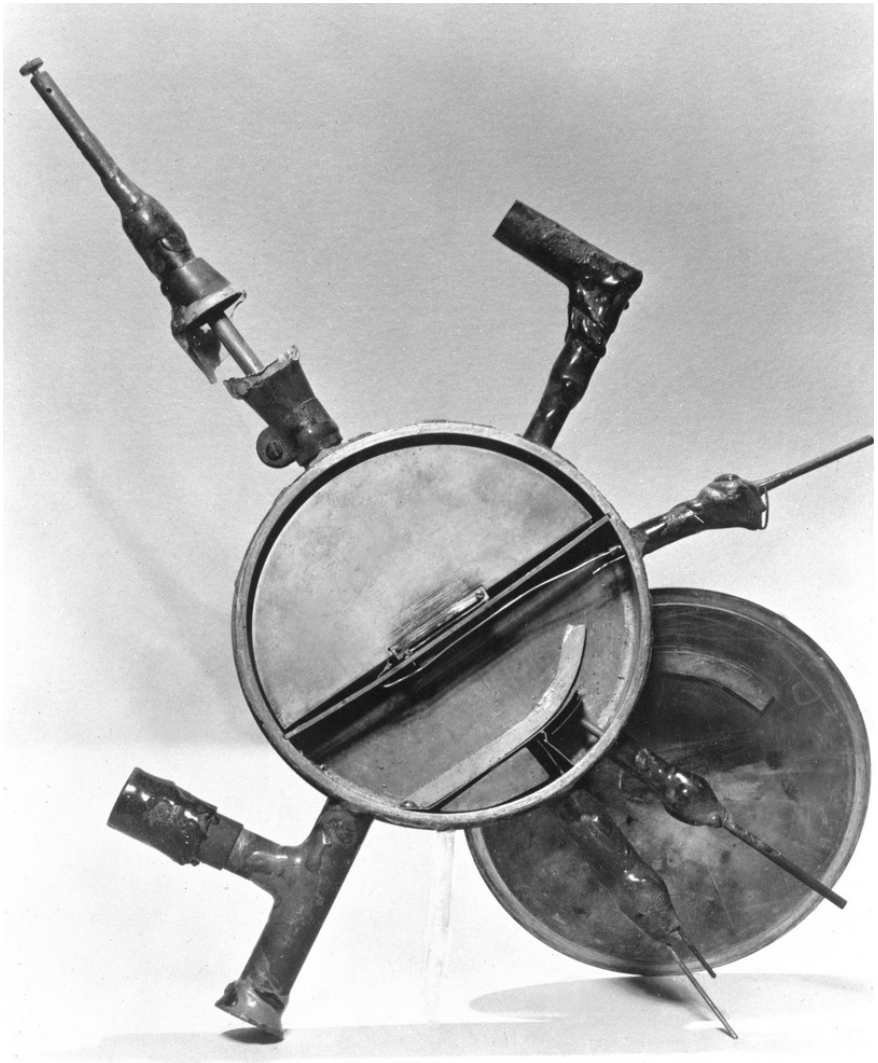


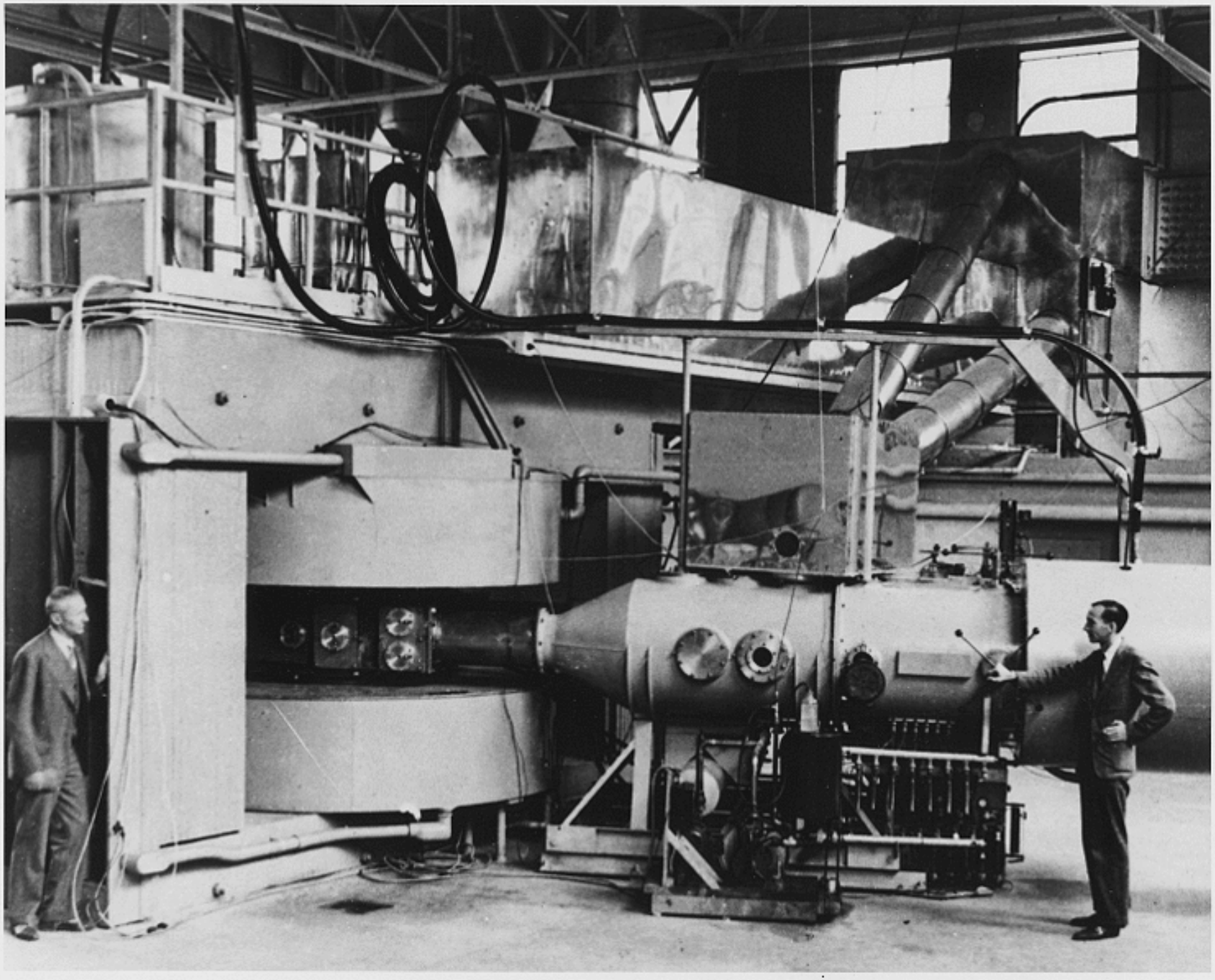
Particle Physics

- Cosmic radiation was discovered around 1910 by Theodor Wulf (1868-1942) and Victor Hess (1883-1964).
- Cloud and Bubble chambers were developed by Charles Wilson (1869-1959) and Donald Glasner (1926-).
- Ernest Lawrence (1901-1958) developed the cyclotron for accelerating protons.
- After WWII, high energy particle physics became a major field of study.

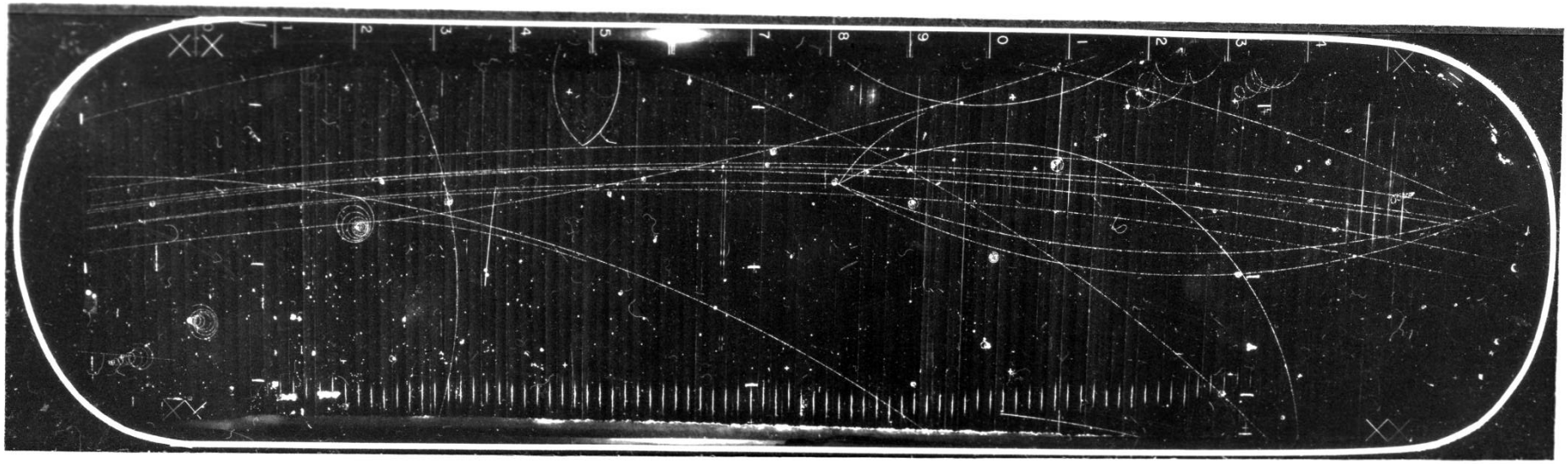
The cyclotron

- This is the first, 5 inch, cyclotron.
- It spins photons around in a spiral at greater and greater speeds.
- It can be used to bombard atoms, or bubble chambers with high velocity protons.





The 4-inch bubble chamber, Lawrence National Lab, 1955.



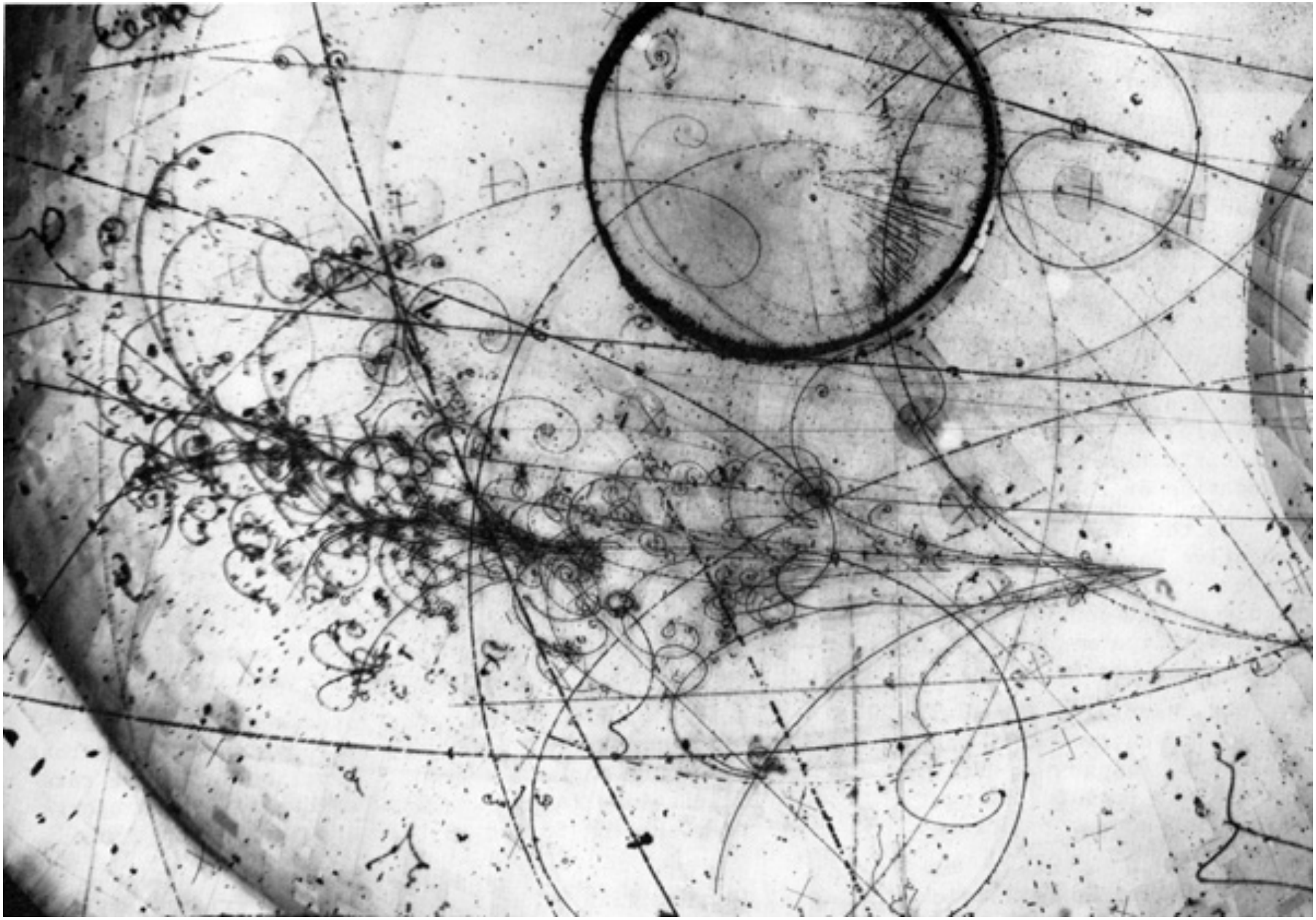
Tracks in the 72-inch bubble chamber, Lawrence Berkeley National Lab, 1981.

Big Labs

- Following the war, high energy physics was organized on the model of “Big Science” - big labs, large staff, huge budget, national or international funding and exposure, etc.
- CERN near Geneva, DESY near Hamburg and Zeuthen, LBL near Berkeley, SLAC near Stanford, Fermilab near Chicago, BNL near New York, KEK in Ibaraki Prefecture, etc.
- There are also many smaller labs and hundreds of research groups around the world.

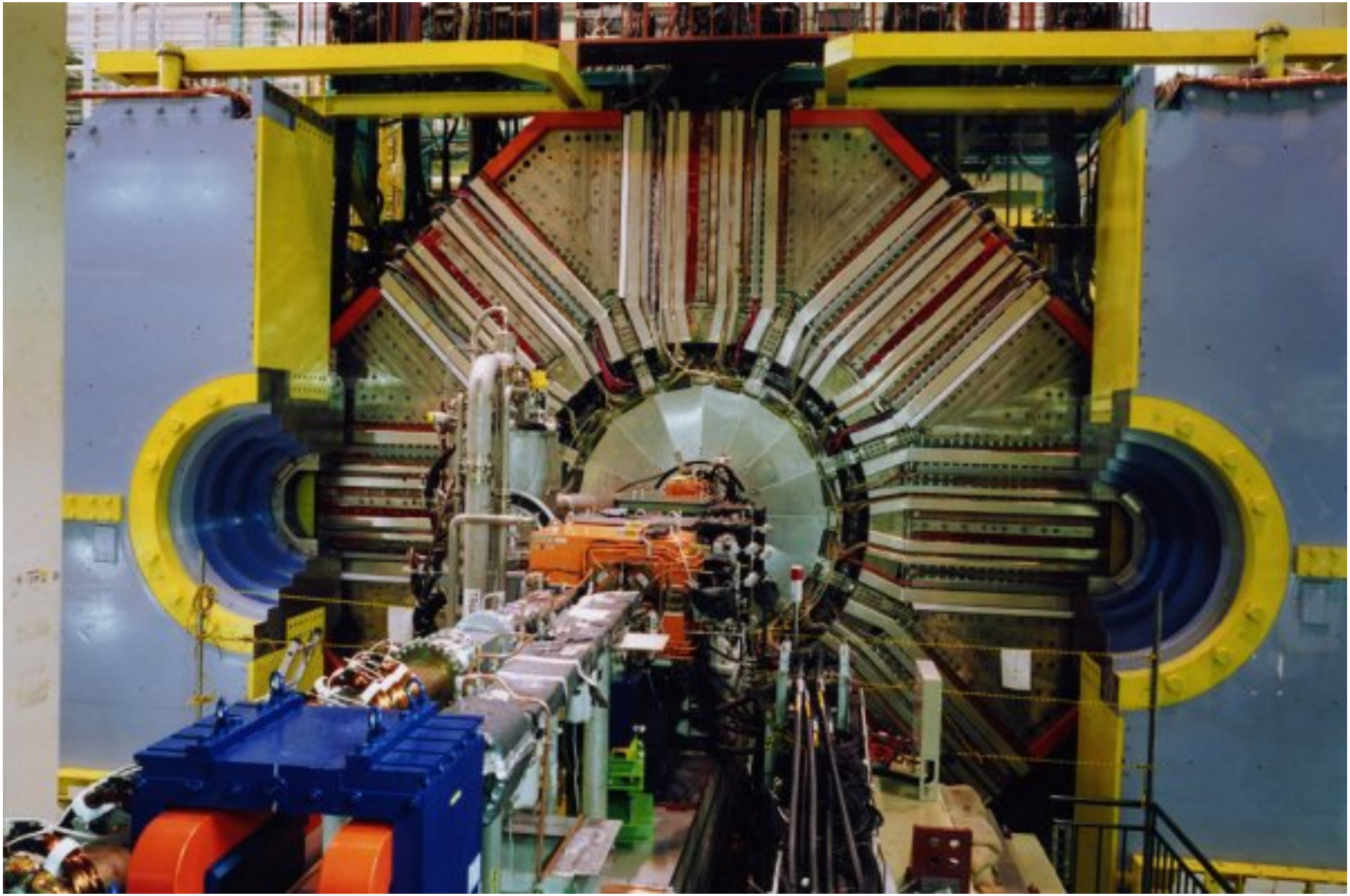
Stanford Linear Accelerator, 2009.

Discontinued bubble chamber at Fermilab, now a sort of sculpture, or monument.



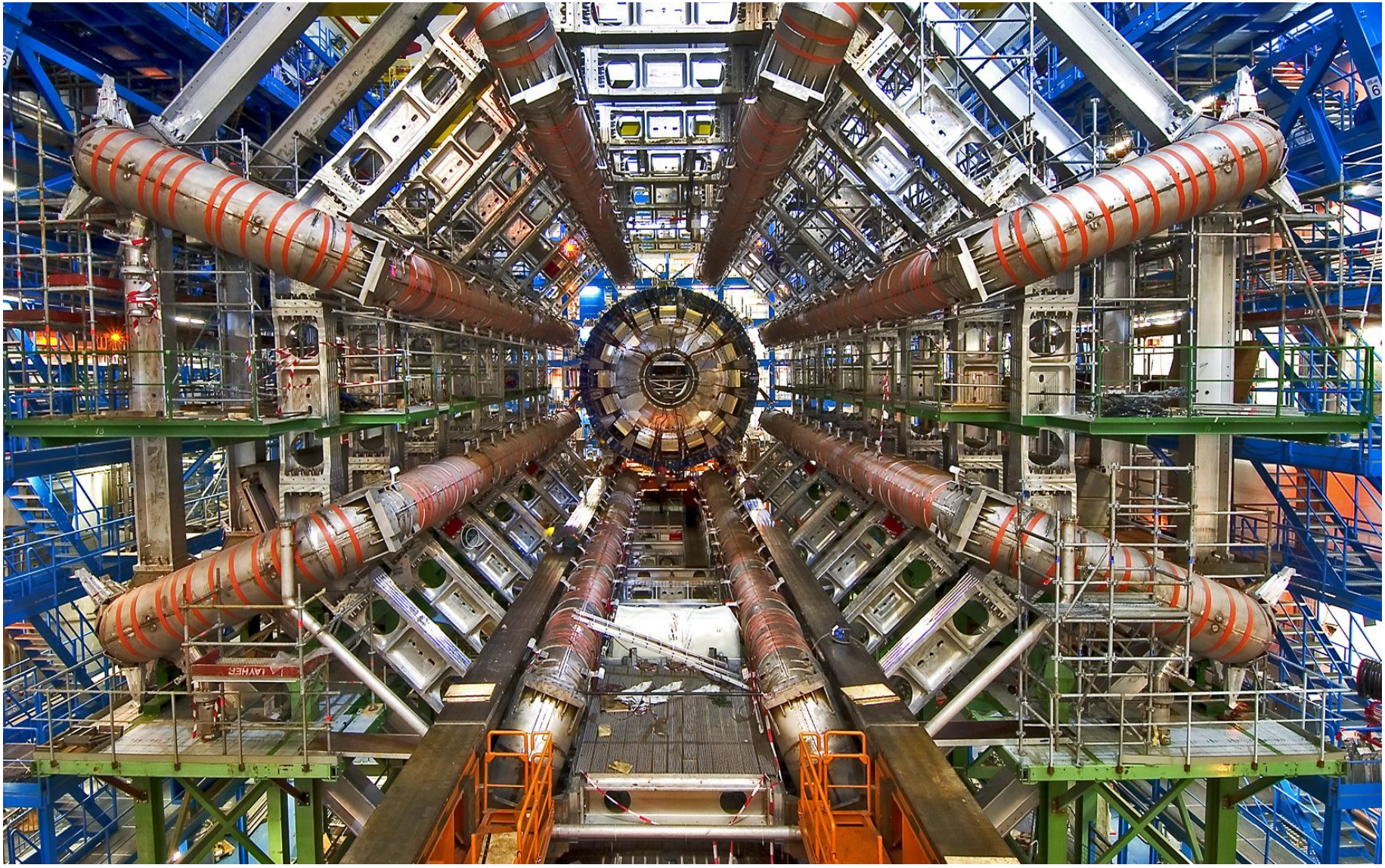
Fermilab, aerial view

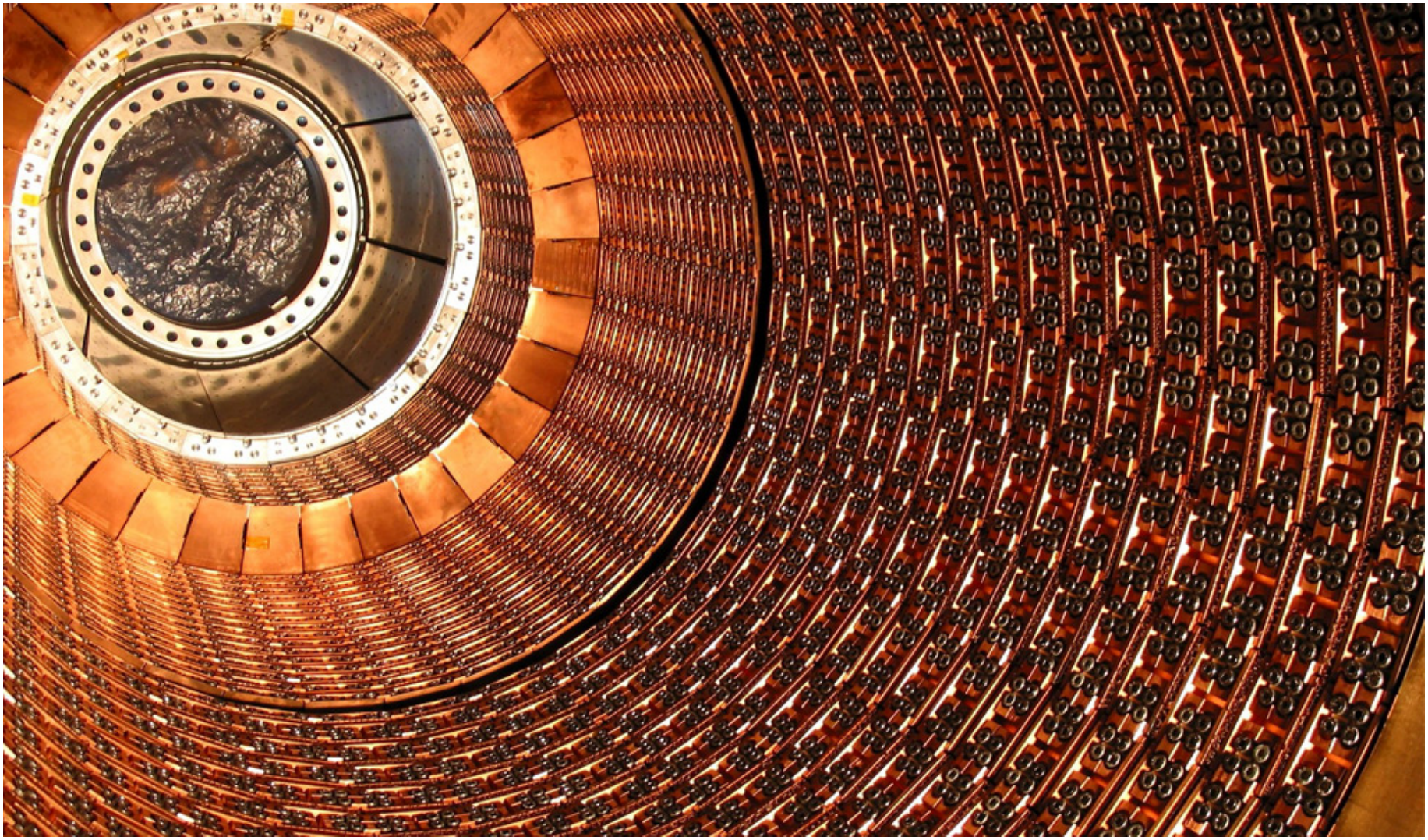
KEK, Tukuba, Ibaraki



CERN, France and Switzerland

The Large Hadron Collider





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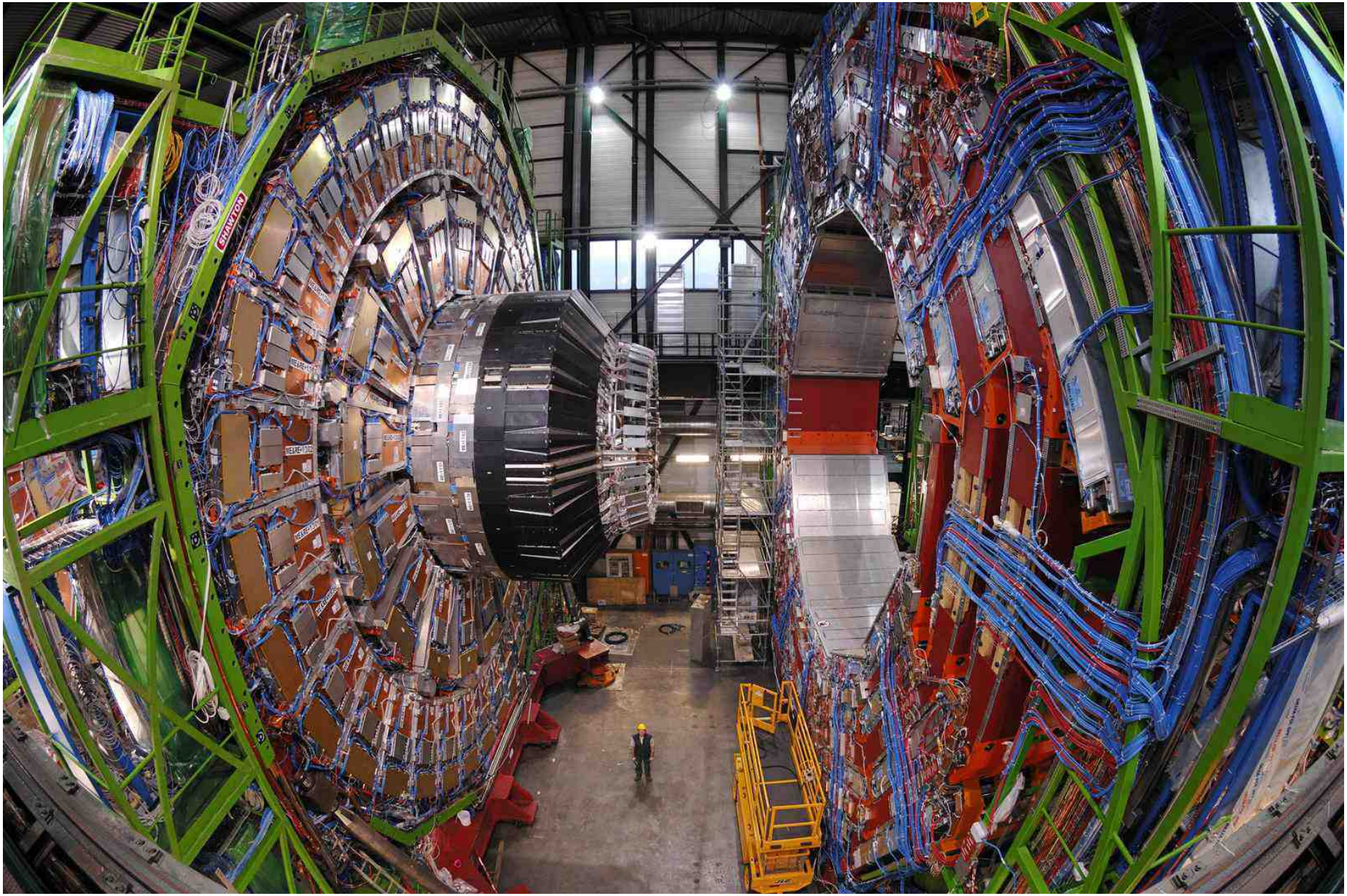
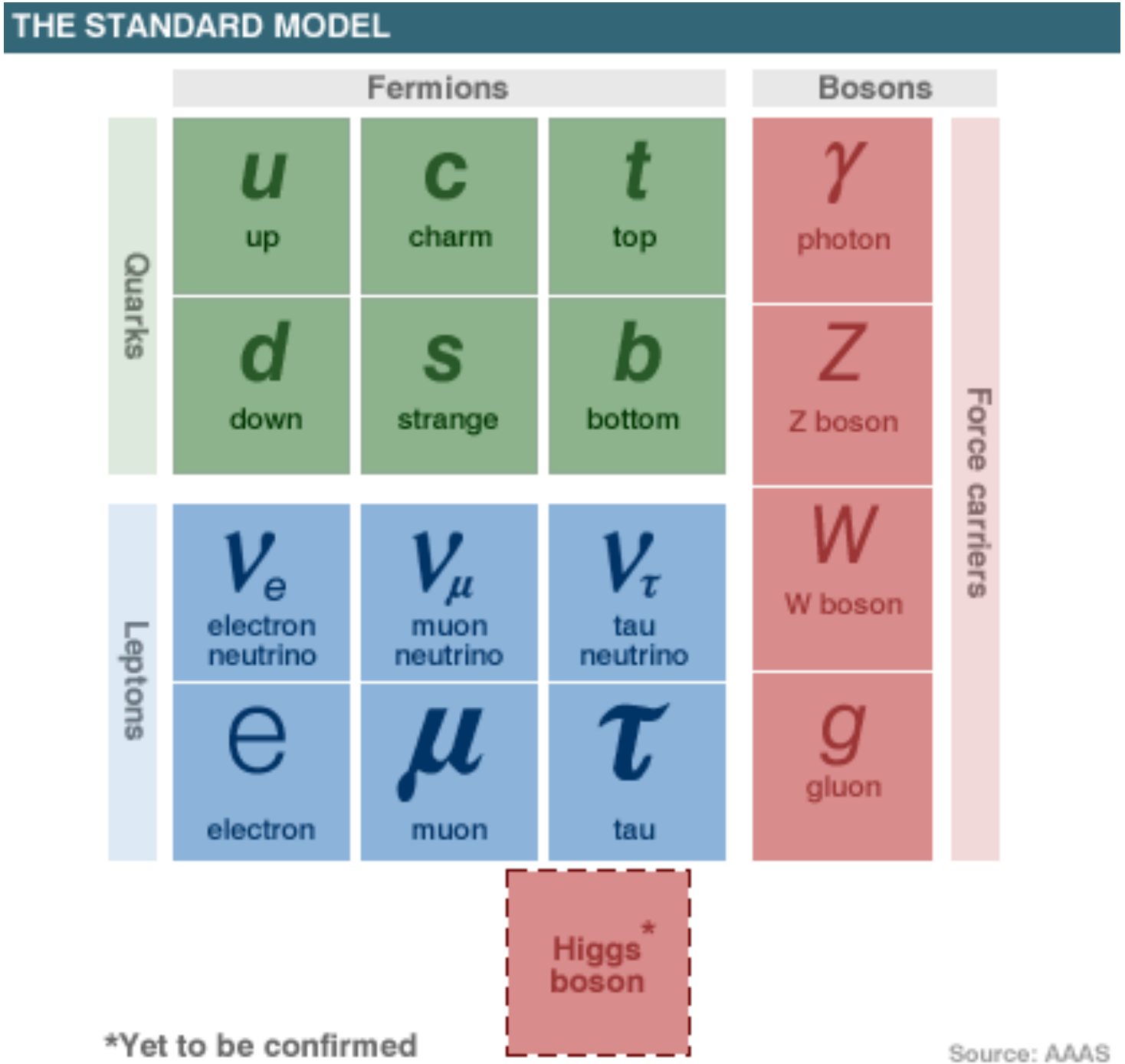

SHANTON

The Standard Model

- Over the course of some 50 years, hundreds of physicists developed a theoretical model of what is happening in these particle events that is known as the *Standard Model*.
- Many of the particles that are apparent in particle collisions are not elementary particles. The standard model describes these apparent particles based on elementary particles.
- Like the periodic table, it display patterns among the elementary particles. It differs, however, in that some of the elementary particles do not exist in free states.
- There are particles that mostly carry mass, particles that mostly carry force and neutral particles that are very small, or maybe without mass.


THE STANDARD MODEL
Fermions
Bosons
Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Leptons
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
e
electron
μ
muon
τ
tau
γ
photon
Z
Z boson
W
W boson
g
gluon
Force carriers
Higgs boson*
*Yet to be confirmed
Source: AAAS

Open Questions

- Why are there three and only three groups?
- What determines the mass/energy of the various elementary particles.
- Does gravity function by the events of a gravity particle (the graviton)? If so, how does this work with the theory of general relativity?

Final Remarks

- In the 20th century, physics has become increasingly abstract, mathematical and secluded from everyday life.
- Quantum theory deals with objects that we never experience directly, but it has led to many of our modern technologies (through solid state physics, quantum chemical bonds, nuclear power, etc.). High energy particle physics has yet to produce specific social benefits, but it is important for cosmology, etc.
- WWII led to a new organization of scientific research, called Big Science.